Characterization of Pipes, Drain Lines, and Ducts using the Pipe Explorer™ System*

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Introduction

As the Department of Energy (DOE) continues to dismantle its nuclear processing facilities, site managers throughout the complex must employ the safest and most cost effective means of disposing or remediating hundreds of miles of potentially contaminated piping and duct work. By their nature, the interiors of pipes and ducts are difficult to access. In many cases, even the exteriors are inaccessible. For example, drain lines are buried or encased in concrete and duct work is often elevated or enclosed. Conducting radiological characterizations of these structures requires significant effort and cost. These costs are further increased if the characterizations are carried out in a radiologically controlled area, where greater personal protective measures and support personnel are required.

Furthermore, for alpha and beta emitting contaminants, such as U-238 and Pu-239, it is necessary to conduct unobstructed measurements of contaminated surfaces. Thus, external measurements through pipe walls are inadequate and the only way to gather accurate data is to get an instrument inside of the pipe.

For these reasons pipes, drain lines, and ducts are problematic when DOE sites are undergoing decontamination and decommissioning (D&D) activities. Without adequate characterization, it is usually necessary to assume the piping is contaminated and to extract and dispose of it accordingly. For buried drain lines this approach can cost on the order of $1,200/ft (Ref. 1) and is often unnecessary as residual contamination levels are below free release criteria.

This paper describes the Morgantown Energy Technology Center (METC) funded program with Science & Engineering Associates, Inc., to develop a solution to the problem of characterizing radioactive contamination in pipes. The technical approach and results of using the Pipe Explorer™ system are presented. This includes the operating principles of the Pipe

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Explorer™ and Alpha Explorer™ systems. It also includes a discussion of the results of surveys using the system during the last year. These field experiences have included the first use of a video inspection system, the first use of the Alpha Explorer™ system, and the first commercial application of the technology. Prior uses of the system are also discussed along with the cost savings that were realized from those uses. An assessment of the status and commercial future of the Pipe Explorer™ and Alpha Explorer™ systems is also presented.

Objective

The objectives for the Pipe Explorer™ development program are divided into two categories as summarized in Table 1. The first category is related to the performance specifications of the system regardless of what type of survey activity is being conducted. The second category of objectives relates to the survey capabilities of the system. The initial survey objective of the Pipe Explorer™ development program was to offer a solution for characterizing gamma and beta/gamma emitting radioisotopes inside of pipes, where the system was to be able to conduct continuous radiological surveys of surface contamination to free release levels. As this aspect of the system was developed and demonstrated it became apparent that there were additional survey techniques that the system was capable of that would be advantageous to the DOE D&D program. For instance, the ability to detect contaminants that primarily emit alpha particles was necessary to make the radiation detection suite of Pipe Explorer™ capabilities complete. Further, the objectives of the development program were expanded to include the ability to conduct video inspections of pipes and to locate buried pipe lines.

Table 1 Objectives of the Pipe Explorer™ development effort.

Performance Objectives	Survey Objectives
• Deploy into pipes 250 feet long • Deploy into pipes 2 to 40 inches in diameter • Deploy sensors into pipes that are 50 percent obstructed • Protect deployed sensors from contamination • Minimize secondary waste generation	• Beta/gamma surveys to free release surface activity levels • Gamma surveys to free release surface activity levels • Alpha surveys to free release surface activity levels • Video surveys to assess pipe integrity • Pipe location

Approach

The Department of Energy (DOE) Morgantown Energy Technology Center (METC) funded SEA to adapt its inverting membrane technology to transport radiation detectors and other characterization tools into pipes. The system uses a pressurized inverting membrane to tow sensors around multiple elbows and through several hundred feet of piping. This technology not only provides an effective transportation method for detectors, but it also provides a clean conduit through which the detector can travel since the sensors are contained inside the membrane. Furthermore, the transparent membrane allows for clear video images to be obtained, while the camera lens is protected from dirt and moisture typically found in pipes.

Technology Description

A. The Deployment System

The primary components of the Pipe Explorer™ technology are illustrated in Figure 1. The heart of the system is an air-tight membrane which is initially spooled inside of a canister. The end of the membrane protruding out of the canister is folded and sealed around the outlet of the canister. When the canister is pressurized, the force from the air pressure on the membrane causes it to be pulled from the spool as the membrane propagates into the pipe by virtue of an inversion process. Thus, as membrane is fed from the deployment canister it travels inside of the membrane that has been deployed ahead of it until it reaches the inversion point. The inversion point continually advances in the pipe. It is the point where the membrane traveling inside of the previously deployed membrane reaches the farthest distance into the pipe and it gently folds out against the pipe wall (Fig. 2).

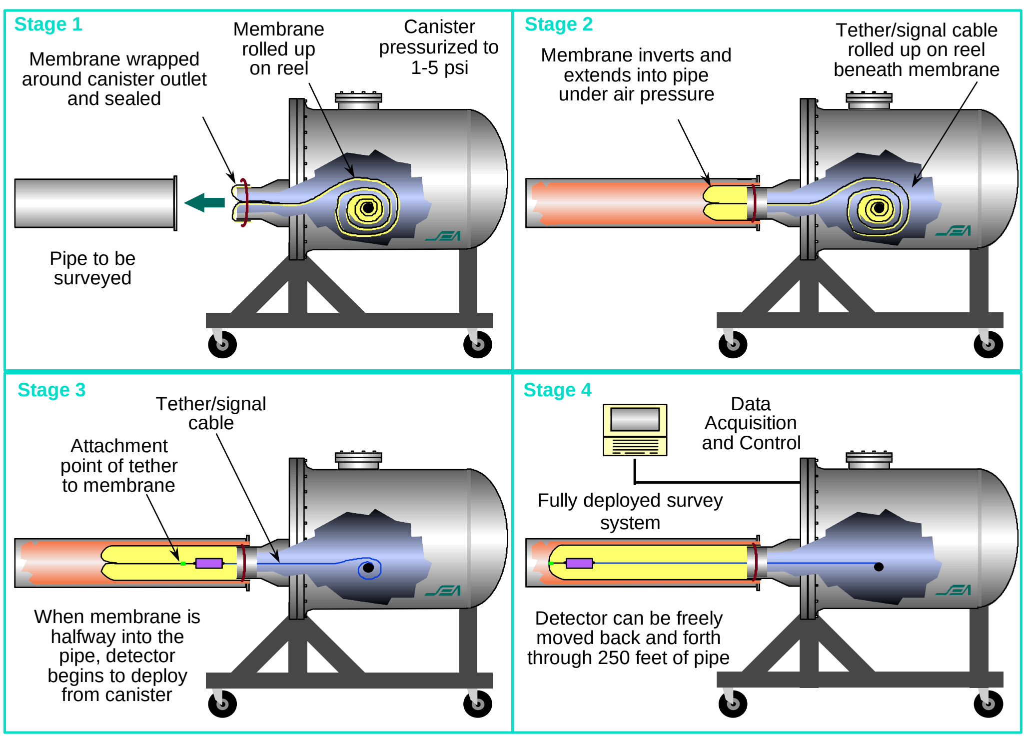

Figure 1. Sketch showing the SEA Pipe Explorer™ system deployment sequence.

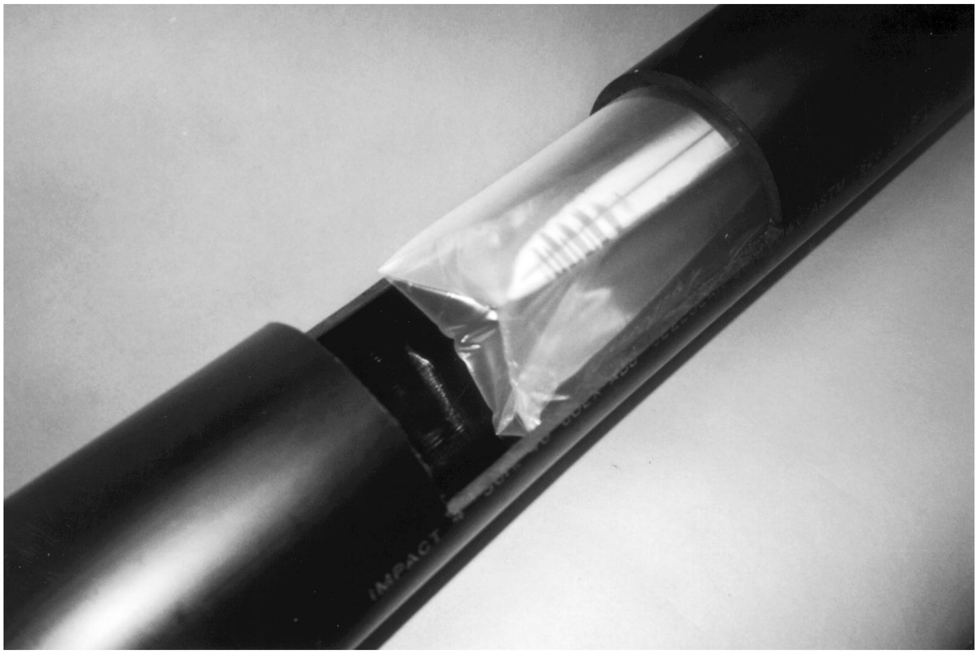

Figure 2. Cut-away view of a Pipe Explorer™ membrane deploying through a pipe, showing the inversion point.

This inversion process continues until the membrane is completely off the spool. At this point the membrane is halfway into the pipe and the distal end of the membrane (where the detector and tether is attached) is at the canister outlet. At this time, a characterization tool, such as a radiation detector, is attached to the end of the membrane and is towed into the pipe as the membrane continues to invert (Fig. 3). The detector cabling is also fed from the spool and towed into the pipe. To retrieve the system, the process is simply reversed, where the cabling, detector, and membrane are wound back onto the spool. The system can thus be used to move a detector freely back and forth through a pipe while the detector output and position are continuously recorded. As a result, the Pipe Explorer™ system provides comprehensive video surveys and detailed characterization of the location and abundance of radioactive contamination in pipes.

The Pipe Explorer™ membrane also provides a clean conduit through which the detector travels. This protects both the detector and the workers handling it. Furthermore, measurements are inherently more reliable. A detector transported in any other fashion runs the risk of removable contamination adhering to the sensor, which can cause erroneously high, or false positive readings.

Use of the Pipe Explorer™ is an extremely clean operation since the only thing to come into contact with the contamination and grime inside the pipe is the membrane. Since the membrane is retrieved through the inversion process, it is turned inside out. Therefore, anything on the dirty side of the membrane is contained. The inexpensive membrane is then disposed. This secondary waste generation is minimal where 200 feet of membrane results in less than 0.5 ft^3 of compacted waste. The cleanliness of the operation can be seen in the photo of Figure 4. This shows the system as it is being used to survey an active sewer line at a DOE site.

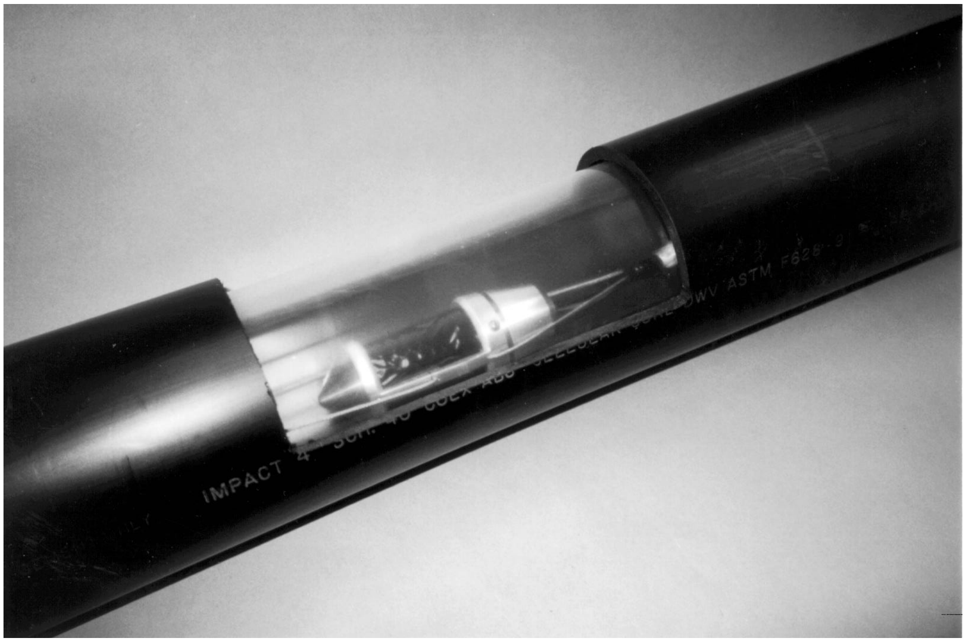

Figure 3. Cut-away view of a Pipe Explorer™ beta/gamma detector deploying through a pipe.

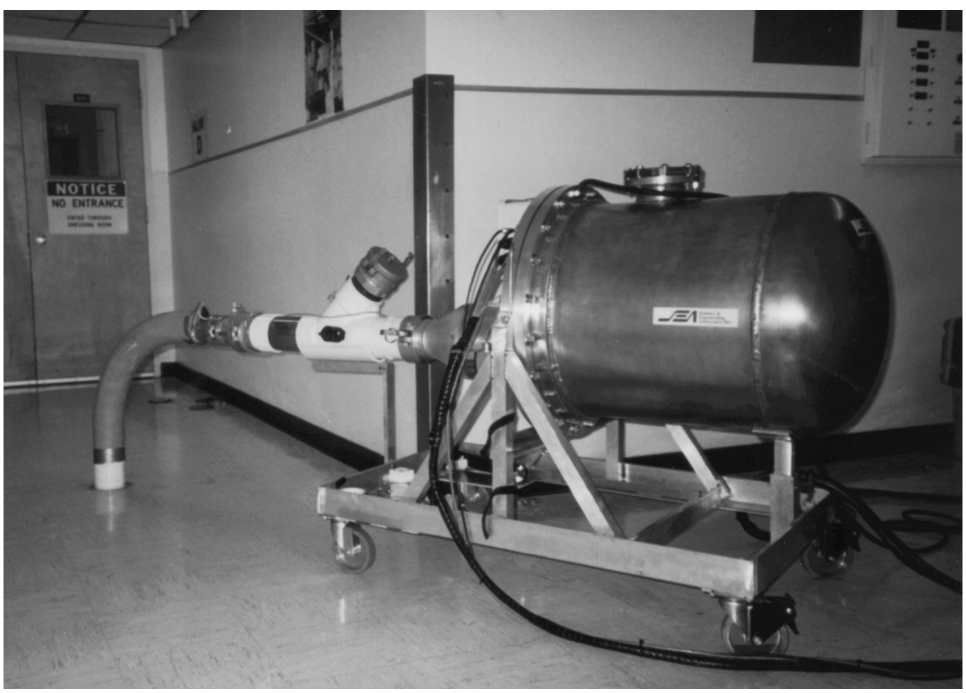

Figure 4. Photo of the SEA Pipe Explorer™ system in use at a DOE site.

B. Characterization Tools

The Pipe Explorer™ system can be used to tow virtually any sensor that is compact enough to fit into a pipe. The tether currently in use has two coaxial cables available (rated to 1 kV) and six single conductor cables which are used to provide power and control to characterization tools. These tools include;

- Plastic scintillator beta/gamma probes
- Photomultiplier tubes for use with the Alpha Explorer™ system
- NaI(Tl) and CsI(Tl) gamma detectors
- Video cameras
- Pipe locator beacons

C. Pipe Explorer™ Output

The typical end product of a Pipe Explorer™ survey is a map of surface activity versus distance into the pipe. Figure 5 shows the results of a beta/gamma survey conducted in a buried drain line where several areas of spot contamination were found. Such data illustrates the importance of transporting a survey detector through a clean conduit provided by the inverting membrane. If the contamination were removable, it would be spread and the localized spots of contamination could not be identified.

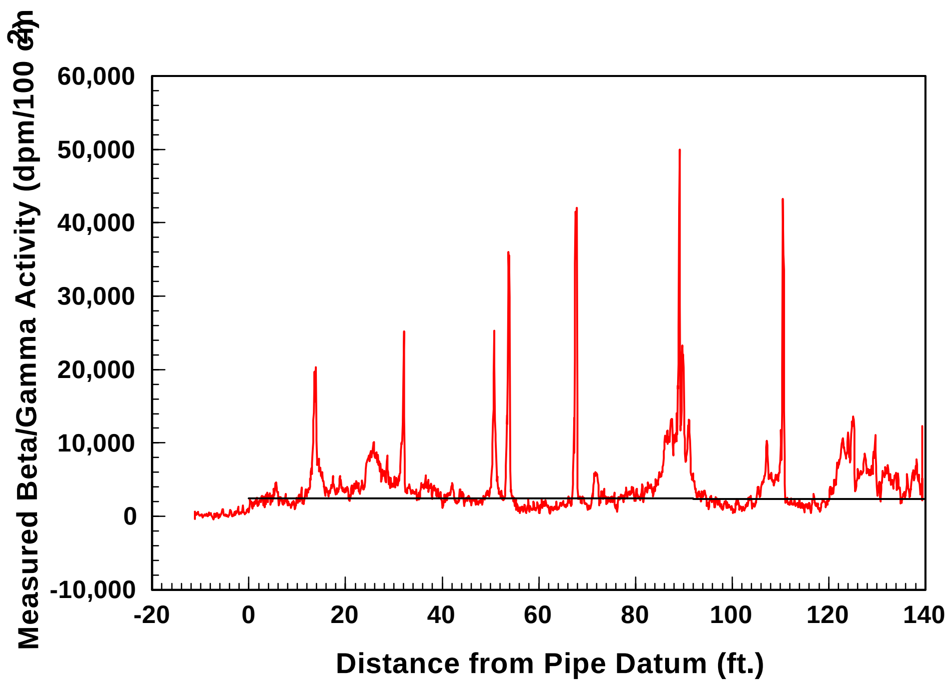

Figure 5. Plot of beta/gamma survey in a drain line at the Grand Junction Projects Office.

D. Recent Sensor Developments

Video Capabilities

Characterization of piping systems and duct work for the purposes of decontamination and decommissioning often requires more than characterization of the levels of residual radioactive contamination. In some instances the exact configuration of the piping system is an important parameter, but is unknown, while in other cases the question that must be addressed is whether or not a piping system has been damaged, allowing potential release of contamination beyond the system itself. To provide answers to these kinds of questions, SEA developed a video camera module capable of being deployed with the Pipe Explorer™ system. The camera module houses a black and white, CCD, pin-hole lens, video camera with a video resolution of 380 TV lines. The camera module was designed to be deployable in 2-inch and larger piping systems. Two different viewing options are available with the camera module. An optional spherical reflector mounted in front of the pin-hole lens offers a wide field of view (180°) allowing close up details of the pipe wall to be observed. With the reflector removed, a forward viewing angle of 59° (horizontal) is provided.

The video signal from the camera module is routed through a character generator to a high resolution video recorder using SVHS format. The character generator is interfaced with a LabView controlled data acquisition system to allow the camera distance, date, time and run ID to be permanently recorded on the video tape. This camera system has been used with success in both demonstrations and commercial applications of the Pipe Explorer™ system.

Alpha Measurement Capabilities

Many potential applications of the SEA Pipe Explorer™ system, such as characterization of residual plutonium contamination in duct work, require measurement of alpha activity. The need for an alpha capability was recognized early in the Pipe Explorer™ development effort. It was, however, also recognized that implementation of this measurement capability would require significantly more development effort than either beta/gamma or spectral gamma measurement capabilities. And so the initial development efforts were focused on adapting existing beta/gamma and spectral gamma measurement techniques to the Pipe Explorer™ system. Once the basic concept of using an inverting membrane deployment system to conduct radiological characterizations of pipe interiors was proven through field demonstrations, work was begun on the development of an alpha measurement capability.

Unlike beta and gamma radiation, alpha particles will not penetrate the 4 mil thick (~100 µm) polyethylene film used for the membrane. For example, the range of a 4.5 MeV alpha particle, through a material of unit density, is approximately 30 µm (Ref. 3). Thus, to successfully incorporate an alpha measurement capability with the Pipe Explorer™, the membrane material itself must be an integral part of the detection system. An effective solution is to make the membrane material a scintillator, and then tow a photodetector through the pipe to detect the scintillation events occurring in the membrane. This is the approach adopted for the alpha measurement capability of the SEA Pipe Explorer™ system, which is referred to as the Alpha Explorer™ system.

This basic measurement approach is shown graphically in Figure 6. When the membrane is deployed inside the pipe, it is inflated, and therefore in intimate contact with the interior surface of the pipe. This places the scintillating membrane in an ideal geometry with the surface to be measured. Any alpha particle emitted from the interior surface of the pipe will necessarily intersect the membrane material, where it can interact with the scintillator, producing a pulse of light. A photomultiplier tube (PMT), connected to standard Nuclear Instrumentation Modules (NIM) counting electronics, is used to detect and count the number of light pulses (alpha activity) as a function of distance into the pipe. In this manner a log of the surface alpha contamination versus distance into the pipe is obtained.

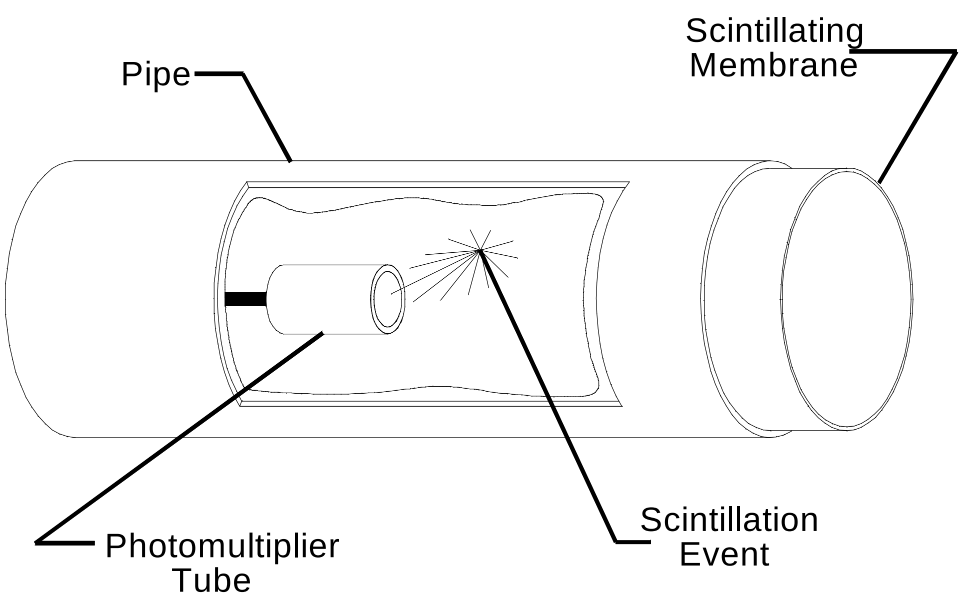

Figure 6. Sketch showing the basic components of the Alpha Explorer™ system.

There are a variety of organic scintillator compounds, such as PPO (2,5 diphenyloxazole), POPOP (1,4-bis-[o-methyl-5-phenyloxazolyl]-benzene), and BBOT (2,5-bis-2-[5-t-butyl-benzoxazolyl]-thiophene) that can be incorporated into plastic materials enabling them to be used as scintillators. There are, however, several drawbacks to this approach. These include the relatively low light yield of plastic scintillators and restrictions that are then placed on the types of plastic that can be used for the base membrane material.

The inorganic scintillator, silver-activated zinc sulfide (ZnS[Ag]), offers an attractive alternative to plastic scintillators. It has a much higher light output than the plastic scintillators, and is insensitive to both beta and gamma radiation. Historically, it has been the scintillator of choice for alpha applications. It is also possible to incorporate ZnS(Ag) into polyethylene films. Because of these properties, ZnS(Ag) was selected over plastic scintillators for use with the Alpha Explorer™ system.

The peak emission wavelength of ZnS(Ag) occurs at 450 nm, which is spectrally well matched to the bialkali photocathode materials commonly employed in PMTs. Additionally, PMTs are available in a variety of sizes and configurations, allowing flexibility in the design of the detector package. Thus, the combination of ZnS(Ag) scintillator and a bialkali PMT provides an efficient alpha detection system for this application.

It is possible to fabricate polyethylene membrane materials with a wide range of ZnS(Ag) concentrations. At very low concentrations of ZnS(Ag), the amount of alpha energy deposited within ZnS(Ag) grains becomes small (more energy is deposited in the surrounding polyethylene) and the detection efficiency drops. Alternatively, at very high concentrations of ZnS(Ag) the detection efficiency is quite high, but the membrane material properties suffer. The burst strength and resistance to tearing drop substantially, rendering these formulations unsuitable for use as inverting membranes. The compromise between detection efficiency and membrane strength lies between these end points.

Another factor that affects detection efficiency is the PMT size, specifically the photocathode area. The scintillation events are isotropic point sources of light. Because of $1/r^2$ intensity losses, as the distance between the scintillation event and the photocathode increases, the amplitude of the pulse from the PMT decreases, eventually to the point that it can not be distinguished from the PMT noise level. Correspondingly, for a scintillation event at a fixed distance, the pulse amplitude increases with the photocathode area. As a practical matter, the best results are obtained with as large a photocathode as can be conveniently fit inside the particular pipe diameter. The prototype alpha detection system was designed specifically for 4-inch piping systems, and utilizes a PMT with a 46 mm diameter (1.8 in) photocathode. All of the data presented in this paper were obtained with this prototype system.

This inverse square relationship between distance of the scintillation event and pulse amplitude from the PMT, dominates the response characteristics of the detection system. If a point source of alpha activity is placed on the bottom pipe wall approximately 2 cm (0.8 in) in front of the photocathode (the optimal solid angle) then an efficiency of approximately 29% is observed, using a membrane with the highest practical ZnS(Ag) concentration. As this source is moved greater distances in front of the PMT, the efficiency falls off rapidly. This effectively defines a response region in front of the PMT. Because the PMT is lying on the bottom of the pipe, there is a small dependence in efficiency on the circumferential position of the point source. Figure 7 shows a surface trend plot of the response surface of the prototype detector in a 4-inch pipe geometry, with the high ZnS(Ag) concentration membrane material. The axial position is the distance along the pipe run length. The circumferential position is the position around the inside of the pipe. Zero is located at the bottom of the pipe, and 16 cm is the top of the pipe, with 4 cm corresponding to approximately 45° of arc.

The data for this figure were obtained as part of a calibration exercise. An Am-241 point source of 216,000 dpm was positioned at a grid spacing of approximately 2 cm by 2 cm. The net

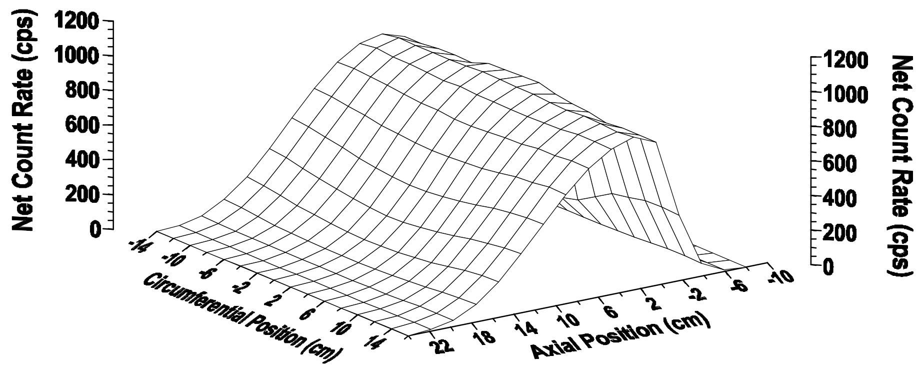

Figure 7. Plot of the response surface of the prototype alpha detector in a 4-inch pipe geometry.

count rate was recorded for each source position. By integrating the observed net count rate, and dividing this sum by the simulated activity density (5.41×10^{6} dpm/100 cm^2), a yield factor of 0.019 cps/[dpm/100 cm^2] is obtained. This yield factor is used to reduce raw net count rate data from surveys to surface activity density (dpm/[100 cm^2]). As can be seen from Figure 7, the response surface of this detector geometry defines a relatively small length segment of the pipe (approximately 15 cm), allowing the system to respond to changing activity levels over short distances in the pipe.

Figure 8 shows an example of the data obtainable with the system. It is a plot of measured count rate versus distance into a pipe from data that was obtained during a field test of the system at the Argonne National Laboratory (ANL) CP-5 reactor. The survey was performed in a 5-inch fuel rod storage tube, where elevated levels of activity were found near the bottom of the tube. The plot shows the results of two surveys of the tube showing the reproducibility of the data.

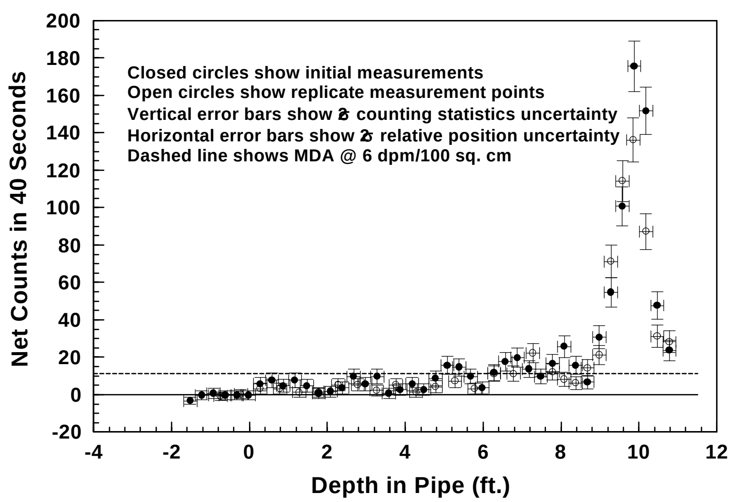

Figure 8. Plot showing the net count data from the initial and replicate surveys performed in Fuel Rod Storage Tube # 30 at ANL CP-5 Reactor.

Accomplishments

The Pipe Explorer™ system has been used during various stages of decontamination and decommissioning of DOE sites. It has been used in the initial characterization stage to determine the extent and location of radiological contaminants. Video surveys have also been conducted to determine the structural integrity and configuration of piping systems. Information from such characterization surveys has been used to guide remedial action plans. The system has also been used to conduct preliminary and post remediation surveys to verify the effectiveness of efforts to clean up contaminated piping.

The Pipe Explorer™ system has been used at five different DOE sites to perform radiological and video surveys of pipes and drain lines. Table 2 lists these sites and the types and lengths of surveys that were performed

Table 2 Chronological listing of Pipe Explorer™ uses.

Site location	Type of piping	Linear Footage	Survey Footage	Types of Surveys conducted
Idaho National Engineering Laboratory	Scrap piping	53	53	• Gamma
DOE FUSRAP Site - Adrian, MI	Buried oil drainage lines	790	790	• Beta/gamma • Pipe location
DOE ALOO Site	Buried drain lines	270	1,200	• Beta/gamma • Gamma • Video
DOE-Grand Junction Projects Office	Buried drain lines	720	1,100	• Beta/gamma • Video
Argonne National Laboratory - CP-5 Reactor	Buried drain lines and fuel rod storage tubes	188	409	• Alpha • Beta/gamma • Video surveys

The Pipe Explorer™ use at the INEL was a feasibility demonstration of the system. The first full scale demonstration occurred at a DOE Formerly Utilized Sites Remedial Action Program (FUSRAP) site in Adrian, MI. This was a highly successful demonstration of the system, where over $1.5 million was saved by the DOE because the Pipe Explorer™ system was used. Details of that use of the system along with a discussion of the cost savings was presented in the proceedings of the 1995 METC technology review meeting.

Since that time the Pipe Explorer™ system has been used at 3 other DOE sites. The first was at a DOE site in New Mexico operating out of the DOE Albuquerque Operations Office

(ALOO). This demonstration was notable in that the video survey capability of the system was used for the first time. Clear images of the interior of 4 and 6 inch diameter pipes were obtained to assess the integrity of the buried pipes. Gamma and beta/gamma surveys were also conducted at the site.

The second use of the Pipe Explorer™ system during the last year occurred at the DOE Grand Junction Projects Office (GJPO). Video surveys were conducted to determine the integrity and layout of buried pipes at the site. Beta/gamma surveys were conducted of a variety of drain lines associated with various buildings involved in the Grand Junction Projects Office Remedial Action Program. In particular, a drain line with a high probability of residual yellow cake contamination buried under a building housing an expensive phone switching system was surveyed and found not to be contaminated. The ability to characterize this buried drain line complements the traditional field surveys of the accessible portions of the building allowing a dose modeling code RESRAD-BUILD to be employed. Results of the RESRAD code indicate that it may be permissible to leave the building with no further action required, thereby avoiding the costly option of replacing the phone system and demolishing the existing building. The final disposition of the building in question has yet to be decided.

The third and most recent use of the Pipe Explorer™ system was part of the Argonne National Laboratory (ANL) CP-5 reactor large scale D&D demonstration project. This was the inaugural use of the Alpha Explorer™ system, which was used to survey several fuel rod storage tubes. Figure 8 shows an example of data obtained from one of the tubes. Surveys were also conducted in an exterior drain line. A beta/gamma detector was used to survey 155 feet of 4-inch clay tile drain pipe. A video survey was also conducted in the pipe. Additional surveys were to be conducted. However, flooding at the site caused damage to some of the equipment.

Benefits

The Pipe Explorer™ system offers many benefits over other pipe inspection approaches, which generally can be classified into one of two categories. The first is rather crude and is referred to as a direct push method. It entails attaching a detector or video camera to the end of a conduit tape or push rod. The tool is then simply shoved into a pipe. The second category encompasses the more sophisticated robotic devices specifically designed as pipe crawlers. Table 3 lists the primary deployment parameters of the Pipe Explorer™ system and these competitive methods. The overwhelming advantage of the Pipe Explorer™ System is that it prevents cross-contamination. Since the towing is provided by the inverting membrane, nothing drags along the pipe wall. The membrane simply folds out along the pipe. Any free material in the pipe is trapped between the membrane and the pipe wall. With direct push techniques and especially with pipe crawlers, free material is pushed ahead of the detector like a snow plow. In addition, the Pipe Explorer™ membrane provides a clean conduit for the detector to pass through. This not only protects the expensive detectors but also ensures that reliable data is gathered.

The next most important advantage of the Pipe Explorer™ system is its ability to overcome obstructions in a pipe. Since the towing force is provided by a flexible membrane, it can maneuver around obstructions blocking over 50 percent of the pipe's cross-sectional area.

Robotic devices move by grabbing the pipe wall. Therefore, there is very little clearance between the robotic hardware and the pipe wall. Thus, even minor obstructions can prevent robotic devices from moving. Three out of the four sites where the Pipe Explorer™ system has been used so far involved surveys of buried drain lines. In all of these surveys substantial debris and scale were present in the pipes. Many 4-inch diameter pipes had effective diameters of about 2 inches in some locations. The Pipe Explorer™ was able to successfully travel through these drain lines and obtain the needed data.

Another notable feature is the maximum deployment speed available with the Pipe Explorer™. While most radiological surveys are conducted at about 3 ft./minute, there is no need to travel that slowly in both directions. The typical mode of operation with the Pipe Explorer™ is to deploy a detector into a pipe at high speed. Detailed radiological measurements are then taken as the detector is retrieved from the pipe at a slower rate. For example, in a 200-ft long survey the detector would be deployed to 200 feet at maximum speed, which would take less than 10 minutes. Measurements would be taken as the detector is retrieved at 3-ft./minute. Thus, it would take a little more than an hour to retrieve the detector. Since typical pipe crawlers are limited to a speed of 3-ft./minute, it would take nearly double the time (and double the cost) to survey a pipe as compared to the Pipe Explorer™.

Table 3. Comparison of Key Features of Pipe Inspection Methods

Technology	Ease [1] Use of	Maximum Deployment Speed	Able to Negotiate Elbows	Able to Negotiate Obstructions	Range of Pipe Diameters[3]	Steerable	Prevents Cross-Contamin-ation
Pipe Explorer™	2	30 ft/min	Yes	Yes	2-40 inches	No	Yes
Typical Pipe Crawler	3	3 ft/min	Yes	No	2-6 inches	Yes	No
Direct Push Techniques	1	Highly variable	No[2]	No	2 inches or greater	No	No

1. Ease of use is a relative ranking where 1 is the easiest to use and 3 is the most difficult.
2. Direct push using a conduit tape can sometimes negotiate elbows, but detectors usually bind up at elbows.
3. Two-inches is given as the minimum diameter for all methods since the limiting factor is usually the detector. For example, Pipe Explorer™ is capable of deploying in ¾-inch diameter pipes. However, there are no high efficiency radiation detectors available that are small enough to go around pipe elbows that small.

Future Activities

During the past year the Pipe Explorer™ system has been significantly improved with the addition of video survey capabilities. Furthermore, the development of the Alpha Explorer™ system has made the suite of radiological survey capabilities of the system complete. The effectiveness of these new additions to the basic Pipe Explorer™ system was well demonstrated during the past year with successful uses of the technology at a DOE ALOO site and the ANL CP-5 reactor large scale D&D project. Given this state of the Pipe Explorer™ and Alpha Explorer™ systems, the development phase of the technology is drawing to a close. Future activities, will thus be focused on transitioning the technology from an EM-50 development project to a main stream DOE survey tool that is used routinely in clean up sites across the country. A good start toward this goal was achieved with the use of the system at the DOE Grand Junction Projects Office, where SEA provided a commercial survey service with the technology. This service was provided under a performance based contract, where the price and subsequent fee that SEA charged was based on the footage of pipe surveyed. The experience gained from the Pipe Explorer™ surveys at GJPO provides the framework for the commercial service business that will continue to be fostered by SEA.

In addition to the DOE, there appears to be a substantial market for the technology in the department of defense and with the nuclear power utilities. SEA is currently forming strategic partnerships to get the Pipe Explorer™ system in use in these markets.

While the primary focus for the Pipe Explorer™ system in the near future will be to develop a service business using the technology, the technological development of the system will not completely stop. Since the basic inverting membrane technology is so versatile, there continues to be opportunities for developing and integrating new instrumentation to address the needs, both within the DOE community and the commercial sector. For instance, SEA has open proposals for developing the capability of using non destructive evaluation (NDE) sensors with the Pipe Explorer™ for detailed assessment of pipe integrity. Heavy metal and VOC sensors are also being investigated as possible additional tools for use with the system. Furthermore, SEA is pursuing concepts for integrating remediation capabilities with the system. This would be an extremely valuable capability to add to the system, since it would offer a more complete remediation service package to site managers responsible for D&D projects with contaminated piping.

Acknowledgments

The development of the Pipe Explorer™ system began in October 1993. Over the next two years the basic system was developed and demonstrated. In 1995 the Pipe Explorer™ contract was amended to include development and demonstration of the Alpha Explorer™ system. The end of the period of performance for the development contract will be in July 1997.

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